

May the force be with
you:
student explanations of
forces on charges in
magnetic fields

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Abstract:

Although physics is the same worldwide, students belonging to different learning systems (or different cultural environments) may develop different styles of approaching and reasoning out physics problems. We compare student physics problem-solving styles between two different student populations: a group of typical American students (from an OSU calculus-based introductory course) and a group of Romanian students (from a second-year class at Bucharest University). We discuss one of the problems given in a small E&M survey, in which students from both populations were presented with a point charge in a region containing a uniform magnetic field. We asked students to determine the force on the charge for different initial conditions. Their answers depend on an understanding of the Lorentz force and their general knowledge from classical mechanics. Observed similarities and differences in approach between these student groups are discussed, and our study's results described.

Raduta has surveyed many E&M misconceptions in the literature in his general paper “[General Students’ Misconceptions Related to Electricity and Magnetism](#),” (OSU, April 2001). He found [seven general classes of misconception](#) discussed in the literature:

- A. Students’ misconceptions related to application of Faraday’s law
- B. Misconceptions related to the interaction between the magnetic field and electric charges
- C. Students failure to recognize important ideas from E&M
- D. Students perception that the electric and magnetic fields are “static” in nature
- E. Misconceptions related to erroneous interpretation of a symbol or due to ambiguous presentations from the textbooks
- F. Misconceptions related to the direction of the Lorentz force and to the application of the right-hand rule
- G. E&M misconceptions related to mechanics misconceptions

Raduta further listed **four areas of student “misconception”** he thought had been missed or understudied in current research:

A. Mathematics-related misconceptions

—e.g., misuse of mathematical tools

B. Tempting analogies between electric and magnetic fields

—e.g., electric field:charge::magnetic field:“charge”

C. Lack of ability to see the connection between Maxwell’s equations and the derived laws

—e.g., Ampère’s law, the Biot-Savart law, Faraday’s law, and Coulomb’s law for the electric forces

D. The geometry of the Lorentz force law

—e.g., \mathbf{F} always \perp to \mathbf{v}

As a result of more thought about this, we decided to determine whether university physics students who had studied E&M really were able to apply the laws governing charges in magnetic fields. Given that Raduta is Romanian, we decided to see whether we could find any difference between students in the two countries.

We tested the ideas of how students in the two countries view the way charges interact with magnetic fields. The problem was presented to 74 students (66 American, 8 Romanian).

The American students were attending a large midwestern university recently involved in winning a national athletic title.

The Romanian students were second year students at the University of Bucharest.

The problem:

We posed the following problem to both American and Romanian students.

You have a charged particle inside a region containing a constant uniform magnetic field.

a) What is the magnetic force (magnitude & direction) acting on the charged particle if the initial velocity is zero? What is the trajectory of this particle?

b) What is the magnetic force acting on the charged particle if the initial speed of the charge is v (known, but unspecified here) and the direction is parallel to \mathbf{B} ? What is the trajectory of this particle?

c) What is the magnetic force acting on the charged particle if the initial speed of the charge is v (known, but unspecified here) and the direction is perpendicular to \mathbf{B} ? What is the trajectory of this particle?

d) What is the magnetic force acting on the charged particle if the initial speed of the charge is v (known, but unspecified here) and the angle between \mathbf{v} and \mathbf{B} is θ ? What is the trajectory of this particle?

The solutions:

a) According to the Lorentz force law, the total force on a charged particle in a region containing electric and magnetic fields is

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

In this problem, $\mathbf{E} = 0$. Therefore, in this region of space,

$$\mathbf{F} = q \mathbf{v} \times \mathbf{B}.$$

Since $\mathbf{v} = 0$, the net force \mathbf{F} is zero. The particle remains at rest.

b) As we found above, in this region of space,

$$\mathbf{F} = q \mathbf{v} \times \mathbf{B}.$$

The cross product of two parallel vectors is zero. The net force \mathbf{F} is zero. The motion continues without change (in a straight line at constant velocity).

The solutions:

c) As we found above, in this region of space,

$$\mathbf{F} = q \mathbf{v} \times \mathbf{B}.$$

The cross product of two perpendicular vectors is perpendicular to both and the magnitude of the cross product is the product of the magnitudes of the vectors. Thus, \mathbf{F} is perpendicular to both \mathbf{v} and \mathbf{B} and

$$F = qvB.$$

Since the force is exactly perpendicular to the velocity, the trajectory is a circle about the axis along which the magnetic field lies.

The solutions:

d) As we found above, in this region of space,

$$\mathbf{F} = q \mathbf{v} \times \mathbf{B}.$$

We may write

$$\mathbf{v} = \mathbf{v}_{\parallel} + \mathbf{v}_{\perp},$$

where v_{\parallel} is the magnitude of the component parallel to the magnetic field and v_{\perp} is the magnitude of the component perpendicular to the magnetic field.

Given the angle θ ,

$$v_{\parallel} = v \cos \theta$$

and

$$v_{\perp} = v \sin \theta.$$

The solutions, (d) continued:

Clearly,

$$|\mathbf{v}_{\parallel} \times \mathbf{B}| = 0$$

and

$$|\mathbf{v} \times \mathbf{B}| = v_{\perp} B = vB \sin \theta.$$

If there is an initial component of velocity along the magnetic field direction, the motion caused by v_{\parallel} goes on without change, while the motion caused by v_{\perp} makes the particle go around in a circle. The nonzero v_{\parallel} means that the plane in which the circle is traced is moving.

Thus, the particle's trajectory is a spiral.

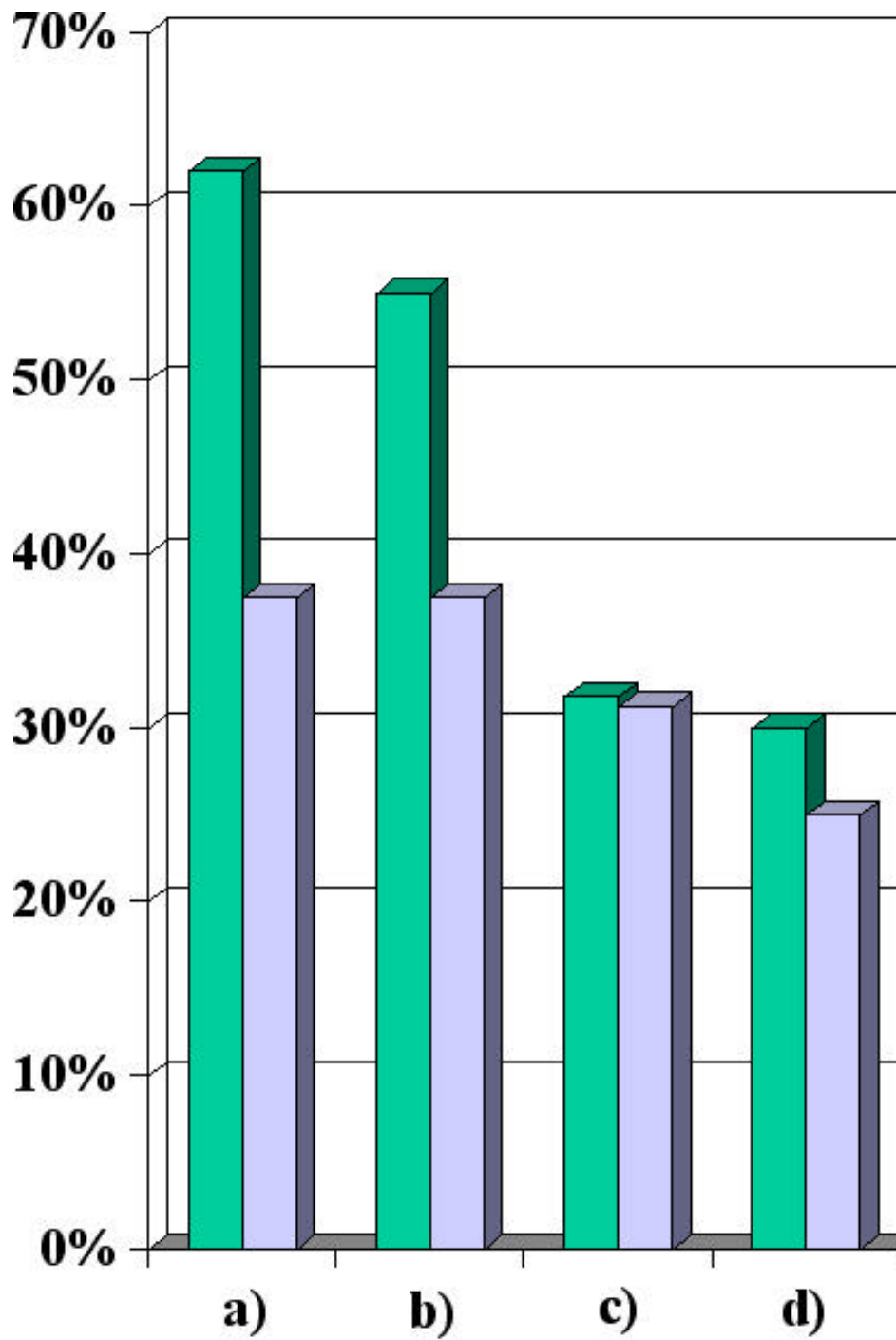
The results on this set of questions are summarized in Tables 1 and 2.

TABLE 1: Students answering each *force* part correctly and incorrectly (or had no answer).

Task	Correct	(%)	Incorrect	(%)
a ($\mathbf{F} = 0$)	60	81%	14	19%
b ($\mathbf{F} = 0$)	58	78%	16	22%
c ($\mathbf{F} = q\mathbf{v}\mathbf{B}$)	42	57%	32	43%
d ($\mathbf{F} = q\mathbf{v}\mathbf{B} \sin \theta$)	44	60%	30	40%

TABLE 2: Students answering each *trajectory* part correctly and incorrectly (or had no answer).

Task	Correct	(%)	Incorrect	(%)
a (at rest)	32	43%	42	57%
b (st. line)	24	32%	50	68%
c (circle)	6	7%	68	93%
d (spiral)	0	0%	74	100%



■ American students' correct answers (%) to Problem 2
■ Romanian students' correct answers (%) to Problem 2

Discussion:

These results from Table 1 show that we physics teachers have had *some* effect on our students in terms of the force acting on a charged particle in a magnetic field. More than half correctly identified the **force** acting in every case.

The results from Table 2 show how **little** effect we have had on our students' overall understanding of the charged particle's **trajectory**.

Romanian student representative (good) answer

a) The magnetic force for a charge in an uniform field is: $\mathbf{f} = q\mathbf{v} \times \mathbf{B}$. If $\mathbf{v} = 0$, then $\mathbf{f} = 0$, and it will not be accelerated in the field, hence we can't speak of direction of the force, but we can say that the magnitude is always zero.

b) $\mathbf{v} \parallel \mathbf{B}$, $\mathbf{v} \neq 0$, $\mathbf{f} = q\mathbf{v} \times \mathbf{B} = qvB \sin \theta$; $\mathbf{v} \parallel \mathbf{B} \Rightarrow \mathbf{v} \times \mathbf{B} = 0$, $\sin \theta = 0$; $\mathbf{f} = 0$; Hence the trajectory is a straight line parallel the lines of magnetic field. The equation of the motion will be:

$$\mathbf{x} = \mathbf{x}(0) + \mathbf{v}t, \text{ where } \mathbf{v} = c\mathbf{t}.$$

c) If $\mathbf{v} \perp \mathbf{B}$, then $\theta = 90^\circ$, $\sin \theta = 1$. The trajectory of the particle will be a circle perpendicular to the magnetic field lines. The magnitude of the force is $f = qvB$, and the direction is that of the radius of the circle pointing towards the center of the circle.

d) $(\mathbf{v}; \mathbf{B}) = \theta$, is the superposition of the two previous cases, and the trajectory of the particle will be a helicoidal one, with parameters radius and step:

$$\text{step} = v(\sin \theta) T; \text{ radius} = f(v(\cos \theta); m)$$

where m is the mass of the particle. The magnitude of the magnetic force is $f = qvB \sin \theta$ and the direction is always perpendicular to the trajectory.

American student representative (good) answer

a) $\mathbf{F}(L) = q\mathbf{v} \times \mathbf{B}$; if $\mathbf{v} = 0$, then $\mathbf{F}(L) = 0$; \parallel to magnetic field

b) $\mathbf{F}(L) = q\mathbf{v} \times \mathbf{B} = qvB \sin \theta = qvB \sin 0^\circ = 0$; across magnetic field

c) $\mathbf{F}(L) = q\mathbf{v} \times \mathbf{B} = qvB \sin \theta = qvB \sin 90^\circ = qvB$, to \mathbf{v} and \mathbf{B} ;

d) $\mathbf{F}(L) = qvB \sin \theta$; \parallel to \mathbf{v} and \mathbf{B} , to \mathbf{v} and \mathbf{B}

Students do not know in many cases what the difference between a scalar or a vector is. In many cases, students would have a scalar in one side of the equation and a vector (or a vector product) in the other side. Even if a student made this mistake, we decided to include them as having a correct answer (if everything else was correct).

The results drawn from this problem are pretty alarming especially if we take into account that this two-question survey—*with two easy standard problems*—was given just two weeks before the end of the quarter, when one would expect students to be pretty comfortable with the main concepts of E&M. (Note: We discuss just the magnetic field problem here. We also asked a Gauss's Law problem.)